MODELING THE CONVERSION OF HYDROACOUSTIC TO SEISMIC ENERGY AT ISLANDS AND CONTINENTAL MARGINS: PRELIMINARY ANALYSIS OF ASCENSION ISLAND DATA

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ABSTRACT

Seismic stations at islands and continental margins will be an essential component of the International Monitoring System (IMS) for event location and identification in support of Comprehensive Nuclear-Test-Ban Treaty (CTBT) monitoring. Particularly important will be the detection and analysis of hydroacoustic-to seismic converted waves (T-phases) at island or continental margins. Acoustic waves generated by sources i or near the ocean propagate for long distances very efficiently due to the ocean sound speed channel (SOFAI and low attenuation. When ocean propagating acoustic waves strike an island or continental margin, they ar converted to seismic (elastic) waves.

We are using a finite difference code to model the conversion of hydroacoustic T-waves at an island or continental margin. Although ray-based methods are far more efficient for modeling long-range (> 1000 km high-frequency hydroacoustic propagation, the finite difference method has the advantage of being able to model both acoustic and elastic wave propagation for a broad range of frequencies. We are performing simulations of T-phases to relatively high frequencies (≥10 Hz). Of particular interest is to identify factors that affect the efficiency of T-phase conversion, such as the topographic slope and roughness at the conversion point and elastic velocity structure within the island or continent. Previous studies have shown that efficient T-phase conversion occurs when the topographic slope at the conversion point is steep (Cansi and Bethoux, 1985; Talandier and Okal, 1998). Another factor impacting T-phase conversion may be the near-shore structure of the sound channel. It is well known that the depth to the sound channel axis decrease in shallow waters. This can weaken the channeled hydroacoustic wave. Elastic velocity structure within the island or continent will impact how the converted seismic wave is refracted to recording stations at the surfa and thus impact the T-phase amplitudes.

For this meeting we will focus on modeling T-phases observed by the May 1999 Ascension Island Experiment. A network of broad-band seismometers on Ascension Island recorded a large number of off-shore airgun shots. The shots occurred at all azimuths around the island and at ranges from 1-45 km. Measurements of signal amplitude and duration will be made to understand the variability of T-phase behavior on Ascension Island. The sensitivity to topographic slope and island structure will also be investigated.

Key Words: T-phase, hydroacoustics

OBJECTIVE

Hydroacoustic monitoring for the Comprehensive Nuclear Test Ban Treaty has made use of some existing hydroacoustic stations that were not necessarily intended to be used for the purpose of CTBT monitoring. Some of these systems are very old with poor knowledge of the sensor calibrations and location in the ocean. The calibrations of T-phase stations -- seismic stations on an island that conduct hydroacoustic monitoring for the CTBT through T-phase signals -- are also poorly understood, making it difficult to utilize such stations effectively in a network of monitoring stations. Finally, although many recognize the possible benefits of joint analysis of different monitoring technologies such as seismic, hydroacoustic, and infrasound, little effort has been expended on this topic, in part because there is not much data of this type to analyze and in part because it is not clear exactly how to analyze it.

The Ascension Island Experiment was an attempt to gather data that could be used to understand all of these technical issues. The experiment would specifically locate and calibrate the CTBT hydroacoustic monitoring station at Ascension Island, help determine how to calibrate T-phase stations, and would leave behind a continuous monitoring system consisting of nearly co-located seismic, hydroacoustic, and infrasound stations. It represented an experiment of opportunity through collaboration and cost sharing. Participant institutions included Cambridge University, Naval Research Laboratory, Scripps Institute of Oceanography, Los Alamos National Laboratory, and the Provisional Secretariat. This paper outlines the specifics of the experiment, features of the data set collected, and plans for future data processing and analysis.

RESEARCH ACCOMPLISHED

Ascension Island is located in the middle of the South Atlantic Ocean at about 8 degrees south latitude (see Figure 1). It was chosen as the location for a hydroacoustic experiment because of an existing hydroacoustic monitoring station on the island, characteristics typical of T-phase stations, and a ship of opportunity with cost sharing potential that would transit the region. The Ascension island experiment was conducted in May-99 after an intensive but relatively short planning period that began in December-98 at a small workshop held at LLNL. The experiment consisted of a sea-based and land-based operation. The sea-based operation (Minshull, 1999) made use of the J.C. Ross, a British icebreaker class oceanographic research vessel returning from a season in the Antarctic via Ascension Island (see Figure 2). The ship was equipped with an array of airguns and hired for four days of airgun shooting and instrument deployment around the waters of Ascension Island. The ship track for the duration of the experiment is shown in Figure 3. A single airgun was deployed for the hydrophone calibrations but the bulk of the experiment utilized an 11-element array of airguns with a total firing chamber size of over 6000 cubic inches. Two temporary hydrophone systems were deployed by Scripps and one by Cambridge. Cambridge also deployed numerous sonobouys during the experiment. In addition several imploding sphere sources were tested.

The land based operation consisted of continuous recording from ten temporary seismic stations deployed on the island for the duration of the airgun shooting. The seismic stations were sited and permitted on an earlier site-survey visit to the island. Concrete pads were poured to provide good coupling and a stable surface for seismometer leveling and the seismometers were buried below ground level. A Sprengnether S-6000 3-component 2 Hz seismometer was emplaced at each station site and recorded continuously at 250 samples/sec with 24 bit digitization using a Reftek data acquisition box. The distribution of stations on the island is shown in Figure 4. The station locations represent a compromise between having multiple lines of stations crossing the island and siting in areas of good relative coupling to competent formations.

HYDROACOUSTIC CALIBRATION:

The three hydrophones currently utilized by the pIDC as the Ascension Island hydrophone monitoring station are ASC26, ASC23 and ASC24. ASC26 is located about 100 km south of the island while ASC23 and ASC24 are within 3 km of each other and only a few km south of the island. The J.C. Ross approached Ascension Island from the south and consequently conducted a calibration of ASC26 during the journey to Ascension Island. A single towed 1000 cubic inch airgun was fired every minute at 5 meters depth as the ship sailed on two orthogonal tracks over the nominal coordinates of ASC26. The data set selected for analysis and the corresponding signals recorded by ASC26 is shown in Figure 5. Each open circle represents a shot and the corresponding waveform is shown. The data will be used to determine the precise location of the hydrophone at the time of the experiment to about 20 meters accuracy. It is clear from the moveout on the waveform traces that the nominal latitude of ASC26 agrees well with the data but that the nominal longitude is somewhat to the east of what the data indicates.

In the same way as data was acquired over ASC26, data was collected over ASC23 and ASC24. The ship tracks and firing locations are shown in Figure 6. The accuracy of the location determinations of ASC23 and ASC24 at the time of the calibration is expected to be about 20-50 meters. Although the bulk of the experiment had a fully deployed 11-element array of airguns firing, a single 1000 cubic inch airgun was used for the hydrophone calibrations. The reasons were to minimize the source distribution and to fire a consistent source near each hydrophone. In addition, two calibrated Scripps hydrophones were temporarily deployed during the experiment and the single airgun was fired over these instruments. This data will be used to characterize the source pressure amplitude spectrum which in turn will allow us to determine the unknown amplitude response spectrums for ASC23, ASC24, and ASC26. Data records show clipping of the direct path signal when the source is very close to the ASC hydrophones which will also allow us to determine the clip levels of the ASC hydrophones.

T-PHASE STUDIES:

The T-phase studies have yet to be accomplished. The 11-element airgun array fired every minute for about 2.5 days, over 3500 events in all. The nominal 20 meter depth of the towed airgun array was constrained by equipment limitations and operational procedures. This depth is very shallow for good coupling to the SOFAR. Consequently, the relatively poor coupling of the airgun events into the SOFAR and the relatively high background seismic noise levels typically encountered on islands may make it difficult to use the airgun as a signal source for T-phase coupling-to-land studies. A plot of the seismic station SBC recordings over a one hour time period during the full airgun array shooting is shown on Figure 7.

A simple model based on the bathymetry and sound speed profile at Ascension Island predicted that for a shallow source, the convergence length for optimal detection of the signal in the SOFAR channel is 45 km. The ship tracks were chosen to provide a few straight line paths from 45 km or more towards a land sesimic station and a MILS hydrophone so that the convergence length can be measured. These data will be compared to model predictions.

During the short duration of the experiment several apparent volcanic events were recorded by the MILS hydrophones, the temporary hydrophones, and the seismometers on the island. An example of the events as recorded on the MILS hydrophones is shown in Figure 8. The events are rich in high frequency energy (above 30 Hz) and are also recorded on land with significant energy above 30 Hz. These events, therefore, will be ideal to address two of the T-phase research issues: 1) How well do the high frequencies in an explosive generated T-phase couple into land? and 2) What is the attenuation of high frequency T-phase energy across an island? The volcanic events recorded appear to be part of a volcanic cycle noticed on the MILS hydrophones about a month before the experiment, a cycle that may correlate with a large fish kill and temperature rise in the waters around Ascension Island during the same time period.

IMPLODING SPHERE SOURCES:

Use of explosives aboard the J.C. Ross was not allowed, consequently there was no commercially viable way to get sources at the SOFAR channel depth (nominally 750 meters) for optimal T-phase signal generation. This left few alternatives since airgun and other seismic marine sources are designed for use only at shallow depths. The result was a rushed attempt to develop an imploding sphere source that could be initiated at a prescribed depth, nominally 750 meters. Imploding spheres have long been recognized (Issacs, 1952 and Orr, 1976) as an effective source at mid-ocean depths and below, however, they have not been reliable: either failing well below or above the desired depth or not failing catastrophically at all (Sauter, 1996).

We designed and tested a prototype smashing system (Boro, 1999) that would initiate sphere failure at a desired depth. The system firmly held the sphere in place and in contact with a 4 inch diameter piston. A 1/4 inch diameter ram connected to the center of the piston passes through a small O-ring sealed hole in the cap confining the piston and abutting the glass sphere. The ram initiates failure by punching a hole through the glass sphere. The end cap on the cylinder confining the piston and opposing the ram end cap tapers to a one inch diameter opening with a rupture disk sealed to it. The rupture disk is calibrated to fail within 5% of the calibrated failure pressure, 1000 psi in our tests. Failure of the rupture disk results in an inrush of high pressure water into the air-filled piston chamber, driving the piston -- and attached ram -- towards the glass sphere.

The smashing system was tested on 4 occasions and reliably actuated every time at the nominal rupture disk failure pressure of 1000 psi. The system also successfully punched a hole in a Benthos flotation sphere on each test, however the Benthos did not fail catastrophically except when tested in the lab without the water pressure acting on the body of the sphere. These rugged flotation spheres are too thick-walled to be reliable sources at SOFAR depths (nominally 2,500 ft.) since they do not tend to fail catastrophically. Tests were also conducted with a thinner walled glass sphere made from a standard 22 liter boiling flask. This sphere was not expected to survive to the depths and pressures desired but deep water tests showed the sphere survived to 1600 meters. The combination of this thinner-walled sphere with the smashing mechanism results in a reliable implosive source at a desired depth and with no associated safety concerns in transport or deployment. During the Ascension Island Experiment, only one sphere implosion was initiated, at a depth of 1600 meters. The implosion signal should be recorded on a temporary Cambridge Univ. OBH. The data will be available soon.

SYNERGY:

An operational synergy experiment was left behind on the island after the airgun shooting. Two new stations were established: a high frequency seismic station and an infrasound station. A level cement pad was poured on top of an old cement antenna anchor that extended over two meters into the ground. An S-6000 seismometer was mounted on the cement pad and buried. A nearby Reftek data acquisition system records continuous 3-component data at 250 samples/second and 24 bits resolution. Data tapes are mailed bi-monthly to LLNL.

In the same part of the island -- near Butt Crater -- an infrasound station was established. This station consists of four sensor elements about 100 meters apart in a tetrahedron formation. Each sensor is an aneroid microbarometer with a manifold allowing for six microporous hose extensions. The data is recorded on a Reftek unit identical to that used for the seismic station. A wind speed and direction indicator will be added to give a total of 6 data channels. These data are recorded to DAT tapes and mailed to LLNL on the same schedule as the seismic data.

The continuous data from the three monitoring technologies will be archived. Selected time periods containing noise and events of interest will be extracted with window lengths that span all three technologies for any known event location. These selected time periods will form a data base that will be analyzed for joint noise statistics and specific joint monitoring analysis studies that use two or more of the technologies to improve overall location or identification capabilities.

CONCLUSIONS and RECOMMENDATIONS

Calibration of existing hydrophone stations using a ship-towed airgun with precision GPS timing and location provides accurate location of hydrophones at sea. It can also determine the amplitude response and clip levels of the hydrophones provided care is taken to characterize the airgun source and the source pressure pulse is sufficient to saturate the hydrophones at close range. The airgun data taken at Ascension Island will be used to locate and calibrate the three hydrophones that are currently recorded at the pIDC.

The data collected at Ascension Island will allow us to determine if an airgun array is an adequate source for

T-phase calibrations at an island station. The primary concern with using an airgun for T-phase signal generation is that the airgun needs to be fired at relatively shallow depths and this does not result in good signal coupling into the SOFAR channel. Luckily, during the short deployment at Ascension Island, there were volcanic events recorded that will allow us to investigate the issues of coupling and of T-phase attenuation across the island even if we determine the airgun sources to be inadequate for T-phase studies.

The use of small explosive sources at the SOFAR channel depth is an ideal way to effectively couple acoustic energy into that channel and provide a good source for T-phase studies. It was clear during the planing phase of this experiment that complying with the required procedures necessary to meet most civilian ship explosives handling safety plans is costly and problematic, if indeed permission can be obtained at all. Imploding spheres circumvent these problems and provide an acoustic source at SOFAR channel depths. They are clearly useful for experimentally investigating local hydroacoustic propagation and blockages as well as longer range acoustic travel times. It remains to be determined if the signal amplitude and bandwidth from imploding spheres are adequate for T-phase coupling research and calibration.

The synergy experiment is underway and will collect continuous data from hydroacoustic, seismic and infrasound stations on or near Ascension Island for the next two years. The data collected will provide a large database of background noise and events for the three monitoring technologies.

Hydroacoustic monitoring research has started to focus on calibration and ground truth issues to try to improve event location and identification, as seismic monitoring has effectively done. The data collected at Ascension Island will be a rich source of ground truth data for the topics summarized above and will help determine how to best conduct future hydroacoustic and T-phase calibrations while collecting hydroacoustic ground truth data for the knowledge base.

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Figure 1) The location of Ascension Island is shown by the red dot. Ascension Island is one of the most remote islands in the Atlantic Ocean.

Figure 2) The J.C. Ross was the sea based platform for the airgun array. The ship is an icebreaker class oceanographic research vessel commissioned in the early 1990's.

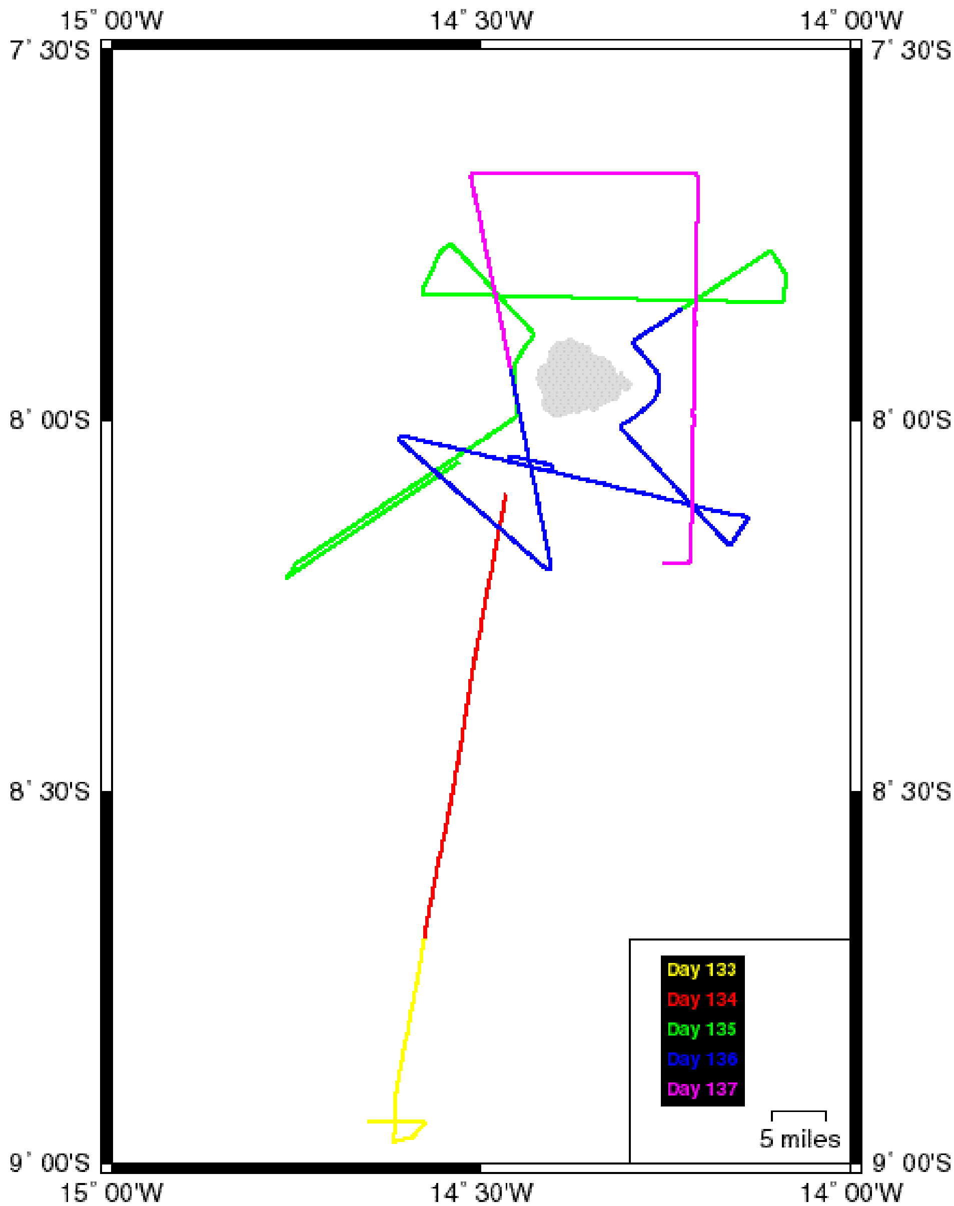

Figure 3) The ship track of the J.C. Ross during the Ascension Island experiment color coded by day. Note that on day 134 the track abruptly ends. This coincides with the end of the single airgun firing followed by a pickup of crew at Ascension Island. The track resumes on day 135 outbound on the southwest extension of the seismic line to 45 km followed by a return on the same track.

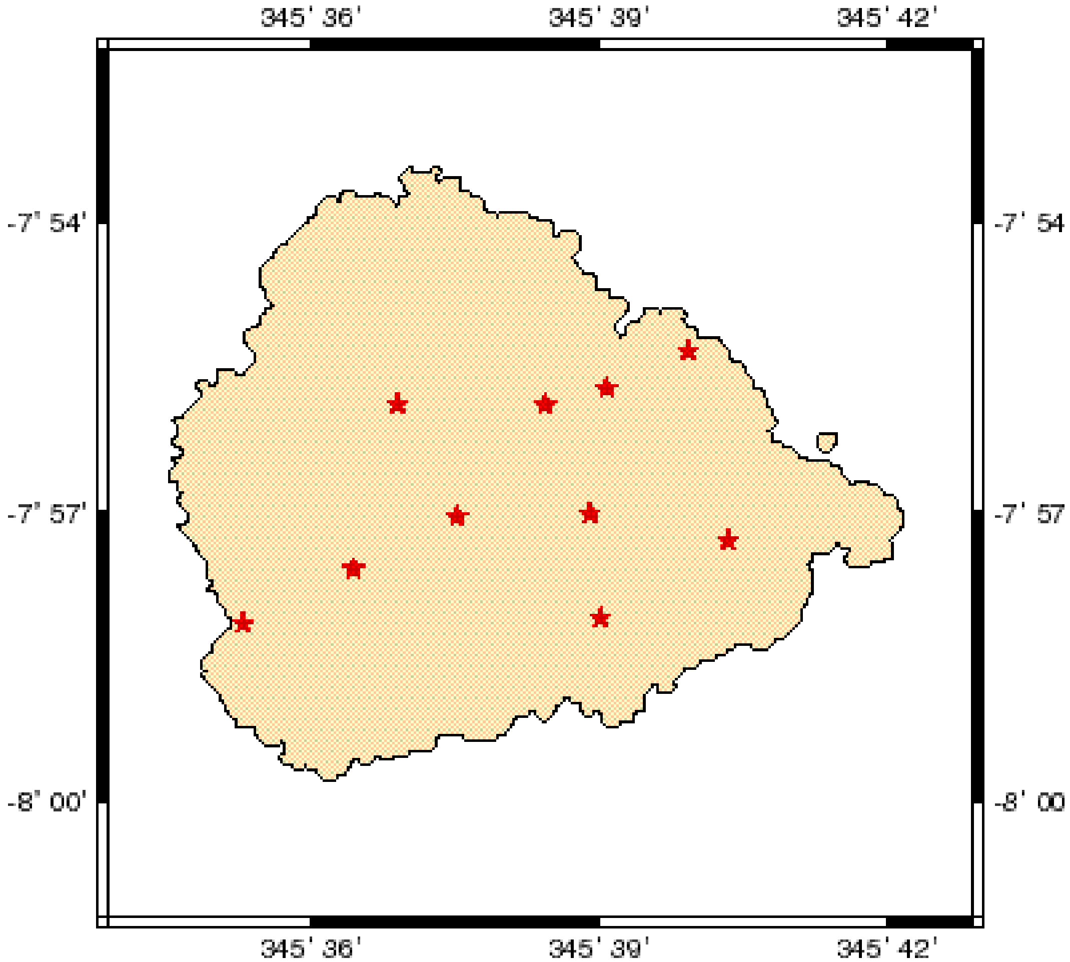

Figure 4) The location of the ten temporary seismic stations on Ascension Island. Note the southwest - northeast trending line of stations that coincide with the extended ship track lines.

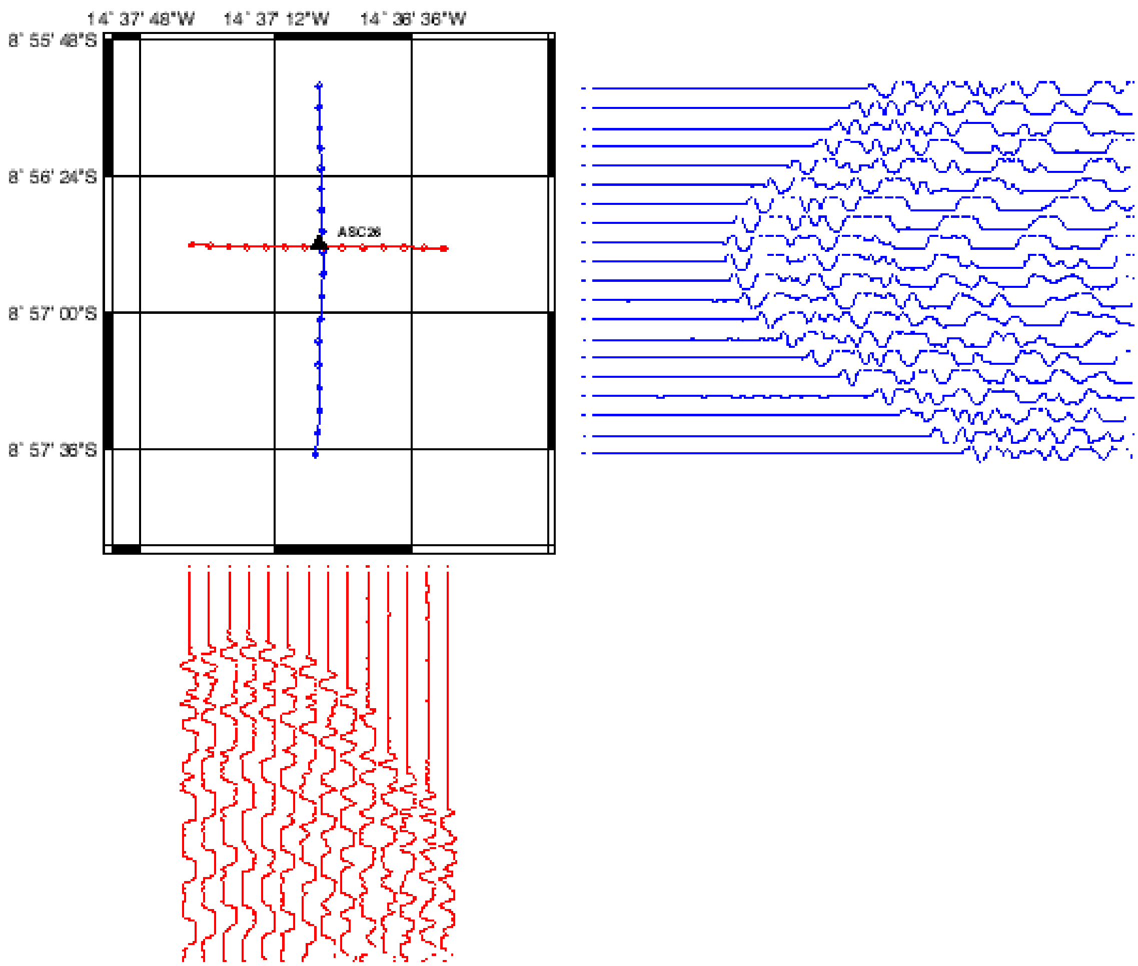

Figure 5) The ship tracks near the nominal location of ASC26 are shown with each shotpoint indicated by an circle. The associated waveforms recorded by ASC26 for each shot are also shown. Note that the data agrees well with the nominal location on the north-south track but the east-wast location of ASC26 is west of the location indicated by the data.

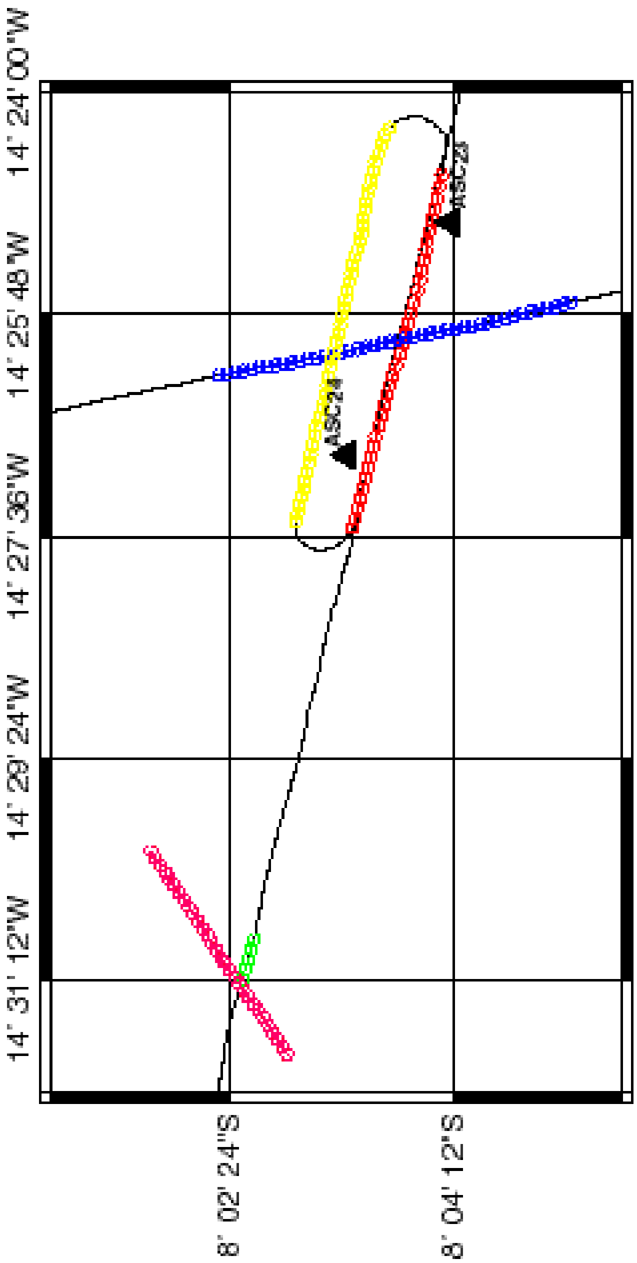

Figure 6) The ship tracks that will be used in the calibration of ASC23 and ASC24 are shown color coded according to day as shown on the ship track file in Figure 3. Note that the tracks displayed to the west are the tracks over the Scripps OBH that will be used to characterize the source.

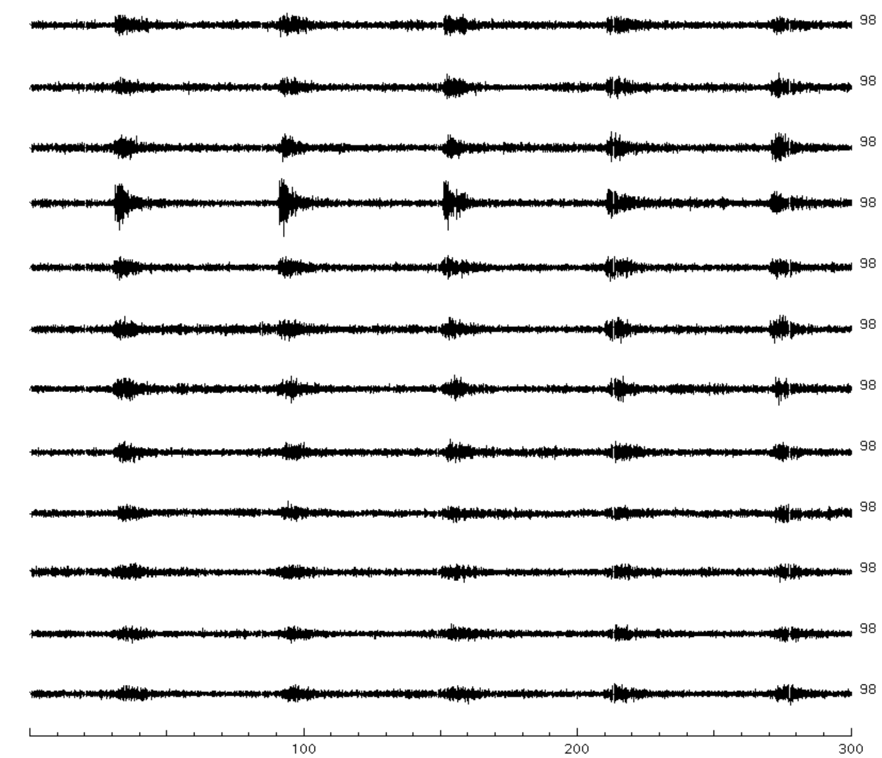

Figure 7) One hour of recordings from seismic station SBC during full array airgun shootings.

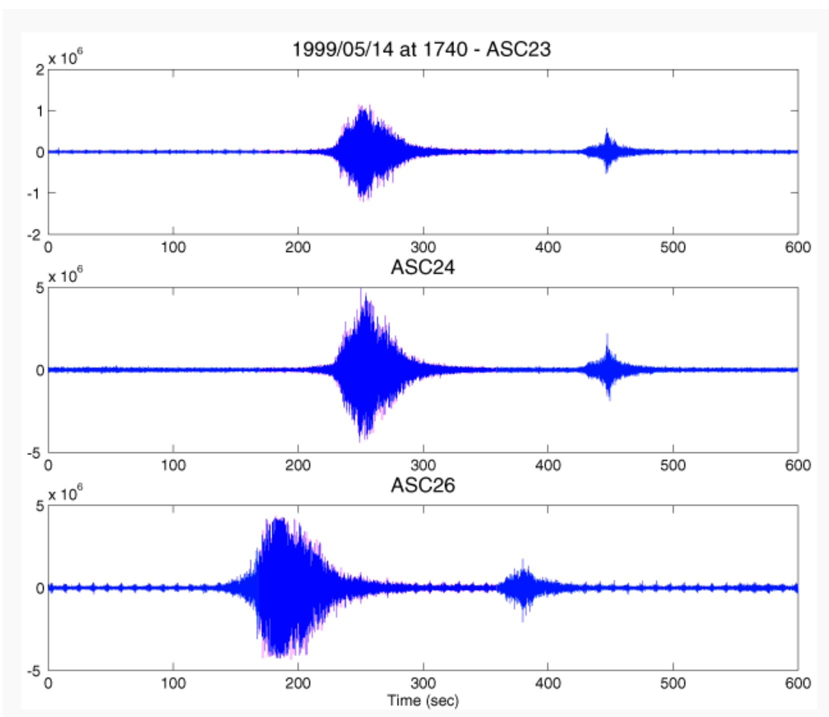

Figure 8) An apparent volcanic event recorded by the MILS hydrophones.